GRB Afterglows in the Deep Newtonian Phase

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Abstract. In many GRBs, afterglows have been observed for months or even years. It deserves noting that at such late stages, the remnants should have entered the deep Newtonian phase, during which the majority of shock-accelerated electrons will no longer be highly relativistic. However, a small portion of electrons are still ultra-relativistic and capable of emitting synchrotron radiation. Under the assumption that the electrons obey a power-law distribution according to their kinetic energy (not simply the Lorentz factor), we calculate optical afterglows from both isotropic fireballs and beamed ejecta, paying special attention to the late stages. In the beamed cases, it is found that the light curves are universally characterized by a flattening during the deep Newtonian phase. Implication of our results on orphan afterglows is also addressed.

IMPORTANCE OF NEWTONIAN PHASE

GRBs have been recognized as the most relativistic phenomena in the Universe. In 1997, Wijers et al. (1997) once discussed GRB afterglows of the non-relativistic phase. However, for quite a long period, many authors were obviously beclouded by the powerfulness of GRBs and emission in the non-relativistic phase was generally omitted. In 1998, Huang et al. (1998) stressed the importance of Newtonian phase for the first time. In fact, the Lorentz factor of GRB blastwave evolves as

$$\gamma \approx (200-400) E_{51}^{1/8} n_0^{-1/8} t_{\rm s}^{-3/8}, \tag{1}$$

in the ultra-relativistic phase. It is clear that the shock will enter the trans-relativistic phase within several months, and will become non-relativistic soon after that. Fig. 1a illustrates the condition clearly. Today, this point has been realized by more and more authors(Livio & Waxman 2000; Frail et al. 2000; Dermer et al. 2000; Dermer & Humi 2001; Piro et al. 2001; in't Zand et al. 2001; Panaitescu & Kumar 2003; Zhang & Mészáros 2003).

MODEL

A refined generic dynamical model has been proposed by Huang et al. (1999), which is mainly characterized by

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{\rm ej} + \varepsilon m + 2(1-\varepsilon)\gamma m}. \tag{2}$$

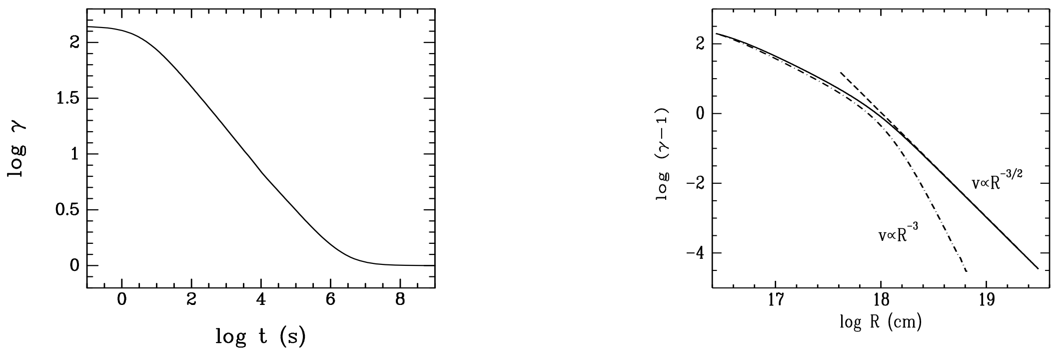

FIGURE 1. **(a)** Left panel, evolution of an adiabatic fireball ($E_0 = 10^{51}$ ergs, and $n = 1$ cm^{-3}, Huang et al. 1998), which becomes non-relativistic in a few months; **(b)** Right panel, Eq. 2 (solid line) is correct in both the relativistic and the Newtonian phases (also see Huang 2000).

Fig. 1b shows clearly that this equation is applicable in both the ultra-relativistic phase and the Newtonian phase. For a realistic description of the overall dynamical evolution of isotropic fireballs and collimated jets, we refer to Huang et al. (1999, 2000a, b).

GRB afterglows mainly come from synchrotron emission of shock-accelerated electrons. In the ultra-relativistic case, these electrons are generally assumed to distribute as $dN'_{\rm e}/d\gamma_{\rm e} \propto \gamma_{\rm e}^{-p}$, with $\gamma_{\rm e,min} \sim \xi_{\rm e}(\gamma-1)m_{\rm p}/m_{\rm e}$. However, we noticed that $\gamma_{\rm e,min}$ will typically be less than 2.0 when $t \geq$ a few months. This means most electrons will no longer be ultra-relativistic in the deep Newtonian phase (Huang & Cheng 2003).

We have suggested that the correct distribution function that is also applicable in the deep Newtonian phase should be (Huang & Cheng 2003),

$$\frac{dN'_{\rm e}}{d\gamma_{\rm e}} \propto (\gamma_{\rm e}-1)^{-p}, \quad (\gamma_{\rm e,min} \leq \gamma_{\rm e} \leq \gamma_{\rm e,max}). \tag{3}$$

In the deep Newtonian phase, most electrons are now non-relativistic and their cyclotron radiation cannot be observed in the optical bands. But there are still many relativistic electrons capable of emitting synchrotron radiation. With the help of Eq. (3), optical afterglows can be calculated conveniently by integrating synchrotron emission from those electrons with Lorentz factors above a critical value ($\gamma_{\rm e,syn}$, Huang & Cheng 2003).

NUMERICAL RESULTS

We present our numerical results in Fig 2. Note that the light curves in Fig. 2a steepens slightly in the deep Newtonian phase. It is consistent with the analytical solution of,

$$S_{\rm R} \propto \begin{cases} t^{(3-3p)/4}, & (\gamma \gg 1), \\ t^{(21-15p)/10}, & (\beta \ll 1). \end{cases} \tag{4}$$

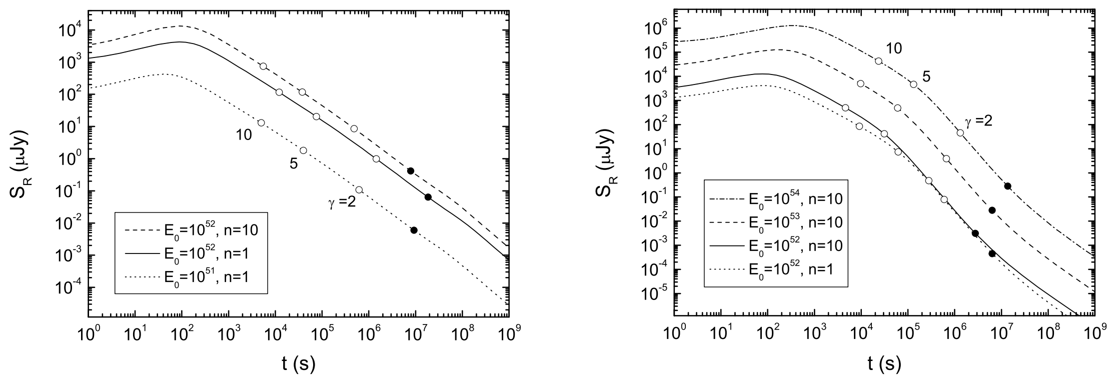

FIGURE 2. R-band optical afterglows from isotropic fireballs (**a**, left panel) and conical jets (**b**, right panel) (Huang & Cheng 2003). Black dot on each light curve indicates the moment when $\gamma_{\rm e,min} = \gamma_{\rm e,syn} \equiv 5$, and open circles mark the time when the bulk Lorentz factor $\gamma = 2, 5$ and 10 respectively.

The light curve in Fig. 2b flattens in the deep Newtonian phase, which is also consistent with the analytical solution (Livio & Waxman 2000),

$$S_{\rm R} \propto \begin{cases} t^{(3-3p)/4}, & (\gamma > 1/\theta_0), \\ t^{-p}, & (\gamma < 1/\theta_0 \text{ and } \beta \sim 1), \\ t^{(21-15p)/10}, & (\beta \ll 1). \end{cases} \tag{5}$$

IMPLICATIONS ON ORPHAN AFTERGLOWS

Orphan afterglows are regarded as a useful tool for measuring the beaming angle of GRBs (Rhoads 1997; Perna & Loeb 1998; Mészáros et al. 1999; Grindlay 1999; Lamb 2000; Totani & Panaitescu 2002; Levinson et al. 2002; Nakar et al. 2002; Granot et al. 2002; Rhoads 2003; Yamazaki et al. 2003). However, Huang et al. (2002) pointed out that there may exist large numbers of failed GRBs, i.e., fireballs with initial Lorentz factors $1 \ll \gamma_0 \ll 100$, which fail to produce GRBs but are likely to give birth to X-ray flashes. The simple discovery of orphan afterglows then does not necessarily mean that GRBs are highly collimated.

To judge whether an orphan afterglow comes from a failed GRB or a jetted but off-axis GRB, a $\log S_{\rm R}$ — $\log t$ light curve will be helpful. However, such a log-log light curve is usually not available for orphan afterglows, since the trigger time is unknown. Fig. 3 illustrates the effect of the uncertainty of the trigger time on the light curve.

To overcome the problem, Huang et al. (2002) suggested that the most important thing is to monitor the orphan for a relatively long period. Obviously, the calculation of afterglows in the deep Newtonian phase is necessary in the studies of orphan afterglows.

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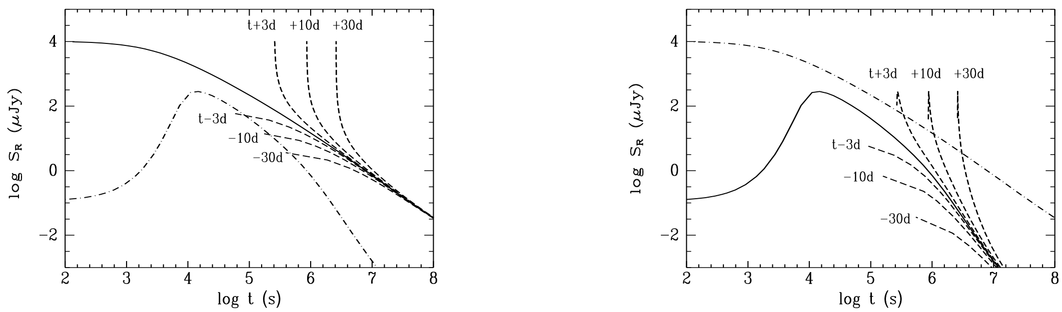

FIGURE 3. Direct comparison of the two kinds of orphan afterglows (Huang et al. 2002). In the left panel, a failed GRB orphan is shifted by $t \pm 3$ d, $t \pm 10$ d, and $t \pm 30$ d to show the effect of the uncertainty of trigger time. In the right panel, a jetted GRB orphan is shifted similarly.

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